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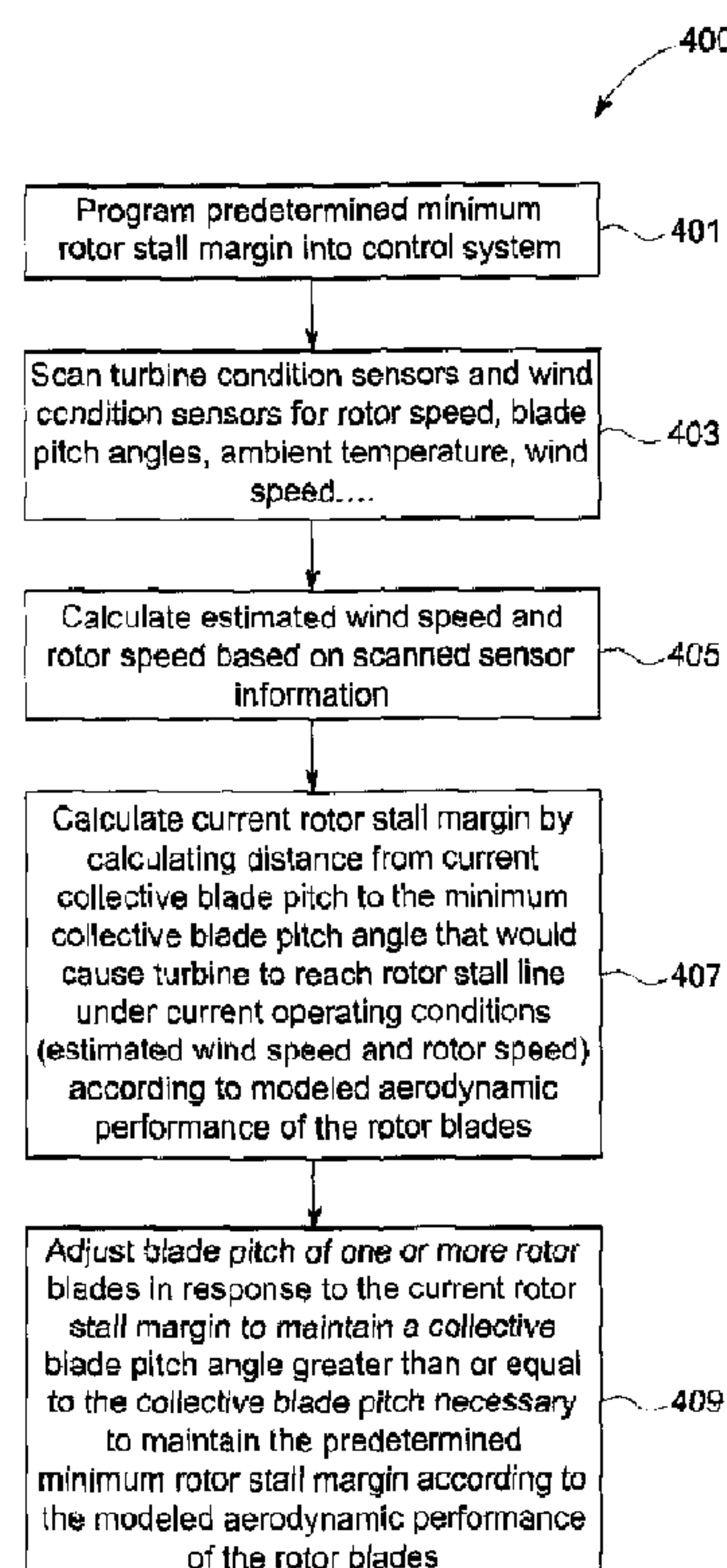
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(57) Abrégé/Abstract:

A method for operating a wind turbine is based on providing a wind turbine that includes a control system programmed to adjust a blade pitch angle of one or more rotor blades without knowledge of rotor blade efficiency. A blade pitch angle of one or more rotor blades is adjusted in response to the current conditions experienced by the wind turbine to provide a blade pitch angle that is greater than or equal to a blade pitch angle necessary to maintain a predetermined minimum rotor stall margin according to modeled aerodynamic performance of the rotor blades such that continuous operation of the wind turbine is maintained without transitions to the stalled mode.

## METHOD OF ROTOR-STALL PREVENTION IN WIND TURBINES

### ABSTRACT

A method for operating a wind turbine is based on providing a wind turbine that includes a control system programmed to adjust a blade pitch angle of one or more rotor blades without knowledge of rotor blade efficiency. A blade pitch angle of one or more rotor blades is adjusted in response to the current conditions experienced by the wind turbine to provide a blade pitch angle that is greater than or equal to a blade pitch angle necessary to maintain a predetermined minimum rotor stall margin according to modeled aerodynamic performance of the rotor blades such that continuous operation of the wind turbine is maintained without transitions to the stalled mode.

## METHOD OF ROTOR-STALL PREVENTION IN WIND TURBINES

### BACKGROUND

**[0001]** The subject matter of this disclosure relates generally to wind turbines, and more particularly to a system and method that utilizes wind turbine models and estimated states to maintain continuous operation of a wind turbine without transitions to a detrimental stalled mode.

**[0002]** Over the last decade, wind turbines have received increased attention as environmentally safe and relatively inexpensive alternative energy sources. With this growing interest, considerable efforts have been made to develop wind turbines that are reliable and efficient.

**[0003]** Generally, a wind turbine includes a rotor having multiple blades. The rotor is mounted to a housing or nacelle, which is positioned on top of a tubular tower. Utility grade wind turbines (i.e., wind turbines designed to provide electrical power to a utility grid) can have large rotors (e.g., 50 or more meters in length). In addition, the wind turbines are typically mounted on towers that are at least 80 meters in height. Blades on these rotors transform wind energy into a rotational torque or force that drives one or more generators that may be rotationally coupled to the rotor through a gearbox. The gearbox steps up the inherently low rotational speed of the turbine rotor for the generator to efficiently convert mechanical energy to electrical energy, which is fed into a utility grid.

**[0004]** Wind turbine blades have continually increased in size in order to increase energy capture. However, as blades have increased in size, it has become increasingly more difficult to control optimum energy capture. The blade loading is dependent on the wind speed, tip speed ratio (TSR) and/or pitch setting of the blade. TSR is the ratio of the rotational velocity of the blade tip to wind speed. It is important to optimize the

operation of the wind turbine, including blade energy capture, to reduce the cost of the energy produced. Pitch setting of the blades (i.e. the angle of attack of the airfoil shaped blade), provides one of the parameters utilized in wind turbine control. Typically, controllers are configured to provide adjustment of rotor speed (i.e., the rotational speed of the hub around which the blades rotate) by adjusting the blade pitch in a manner that provides increased or decreased energy transfer from the wind, which accordingly is expected to adjust the rotor speed.

**[0005]** Wind turbines with sophisticated control systems maintain constant speed and power by active blade pitch control. Power production for a wind turbine is negatively impacted if the blades of the wind turbine operate in a non- optimal state. In addition, low air density or a drop in air density may also result in a loss of energy transfer from the wind to the blades.

**[0006]** Aerodynamic stall causes a decrease in lift and an increase in drag coefficients for a wind turbine blade. The onset of stall is signaled by a sharp change in a wind turbine's performance evident by degradation in output power versus expected power. More specifically, the rotor is said to be stalled if any increase in wind speed reduces the thrust on the rotor. In the event of aerodynamic stall, the energy transfer from the wind is reduced precipitously. Power degradation resulting from the loss of energy transfer is most significant during periods of rated winds where full power output is anticipated by the controller. That is, the control system interprets the decrease in power as a need for increased rotor torque. The control system reacts by calling for a decrease in blade pitch, which increases the angle of attack in an effort to increase the energy transfer from the wind. The increasing the angle of attack by the control system of an aerodynamically stalled blade further increases the flow separation, increasing the stall condition and further decreasing the energy transfer from the wind. As such, the current systems fail to address conditions, such as low density air operation that may cause aerodynamic stalling.

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[0007] Therefore, what is needed is a method for operating a wind turbine that maintains the blade pitch angle at an angle greater than or equal to a calculated minimum pitch angle for a large variety of wind turbine and wind conditions to avoid having the wind turbine rotor enter a stall condition.

#### BRIEF DESCRIPTION

[0008] One aspect of the present disclosure includes a method for operating a wind turbine. The method includes providing a wind turbine having at least one blade having adjustable pitch angle. Wind turbine conditions are measured and wind conditions are estimated for the wind turbine. A minimum pitch angle is determined in response to the measured wind turbine conditions and the estimated wind conditions that would cause the wind turbine rotor to enter a stall condition, according to modeled aerodynamic performance of the rotor blades. A collective blade pitch is then established according to the modeled aerodynamic performance of the rotor blades to ensure a predetermined rotor stall margin is maintained.

[0009] Another aspect of the present disclosure includes a wind turbine comprising at least one blade having an adjustable pitch angle. The wind turbine further comprises sensors for measuring wind turbine conditions and wind conditions. An integrated controller is programmed to calculate a minimum pitch angle in response to the measured wind turbine conditions and the estimated wind conditions that would cause the wind turbine rotor to enter a stall condition, according to modeled aerodynamic performance of the rotor blades. The controller is further programmed to establish a collective blade pitch, according to the modeled aerodynamic performance of the rotor blades, to ensure a predetermined rotor margin is maintained.

[0010] These and other features, aspects and advantages of the present invention will become better understood with reference to the following description and appended claims. The accompanying drawings, which are incorporated in and constitute a part of

this specification, illustrate embodiments of the invention and, together with the description, serve to explain the principles of the invention.

## DRAWINGS

[0011] The foregoing and other features, aspects and advantages of the invention are apparent from the following detailed description taken in conjunction with the accompanying drawings in which like characters represent like parts throughout the drawings, wherein:

[0012] Figure 1 is an illustration of an exemplary configuration of a wind turbine;

[0013] Figure 2 is a cut-away perspective view of a nacelle of the exemplary wind turbine configuration shown in Figure 1;

[0014] Figure 3 is a block diagram of an exemplary configuration is a block diagram of an exemplary configuration of a control system for the wind turbine configuration shown in Figure 1;

[0015] Figure 4 is a process flow diagram of an exemplary method according to an embodiment of the present disclosure; and

[0016] Figure 5 illustrates a typical aerodynamic map of the torque coefficient,  $C_m$ , as a function of the tip-speed ratio and blade pitch angle for a wind turbine blade.

[0017] While the above-identified drawing figures set forth alternative embodiments, other embodiments of the present invention are also contemplated, as noted in the discussion. In all cases, this disclosure presents illustrated embodiments of the present invention by way of representation and not limitation. Numerous other modifications and embodiments can be devised by those skilled in the art which fall within the scope and spirit of the principles of this invention.

## DETAILED DESCRIPTION

**[0018]** Referring to Figure 1, an exemplary wind turbine 100 according to one embodiment of the present invention is disclosed. The wind turbine 100 includes a nacelle 102 mounted atop a tall tower 104, only a portion of which is shown in Figure 1. Wind turbine 100 also comprises a wind turbine rotor 106 that includes one or more rotor blades 108 attached to a rotating hub 110. Although wind turbine 100 illustrated in Figure 1 includes three rotor blades 108, there are no specific limits on the number of rotor blades 108 required by the embodiments described herein. The height of tower 104 is selected based upon factors and conditions known in the art.

**[0019]** In some configurations and referring to Figure 2, various components are housed in nacelle 102 atop tower 104. One or more microcontrollers or other control components are housed within a control panel 112. The microcontrollers include hardware and software configured and programmed to provide a control system providing overall system monitoring and control, including without limitation, pitch and speed regulation, high-speed shaft and yaw brake application, yaw and pump motor application and fault monitoring. In alternative embodiments of the disclosure, the control system may be a distributed control architecture not solely provided for by the control panel 112 as would be appreciated by one of ordinary skill in the art. The control system provides control signals to a variable blade pitch drive 114 according to modeled aerodynamic performance of the rotor blades to control the pitch of blades 108 (Figure 1) that drive hub 110 as a result of wind. In some configurations, the pitches of blades 108 are individually controlled by blade pitch drive 114.

**[0020]** The drive train of the wind turbine 100 includes a main rotor shaft 116 (also referred to as a "low speed shaft") connected to hub 110 and supported by a main bearing 130 and, at an opposite end of shaft 116, to a gear box 118. The speed of rotation of the main rotor shaft 116 or rotor speed may be measured by suitable instrumentation or measurement devices. In some configurations, hub rotational speed is known from an

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encoder 117 on a high speed shaft connected to the aft end of a generator 120. In addition, the rotor speed may be determined from a proximity switch 119 on the high or low speed shaft. In addition, the rotor speed may be directly measured with sensing devices, such as optical strobing detection of a labeled high or low speed shaft. The rotor speed information may be provided to the control system along with other current turbine conditions. Gear box 118, in some configurations, utilizes a dual path geometry to drive a high speed shaft 121. The high speed shaft 121 is used to drive generator 120, which is mounted on main frame 132. In some configurations, rotor torque is transmitted via coupling 122. Generator 120 may be of any suitable type, for example, a wound rotor induction generator.

**[0021]** Yaw drive 124 and yaw deck 126 provide a yaw orientation system for wind turbine 100. According to one embodiment, anemometry provides information for the yaw orientation system, including measured instantaneous wind direction and wind speed at the wind turbine. Anemometry may be based on a wind vane 128. The anemometry information, including without limitation, wind force, wind speed and wind direction, may be provided to the control system to provide inputs for determination of effective wind speed, among other things. In some configurations, the yaw system is mounted on a flange provided atop tower 104.

**[0022]** In addition to rotor speed sensor(s) and wind speed sensors such as described herein, turbine power sensors may be employed to provide the electrical power output level, pitch angle sensors 123 may be employed to provide individual and collective blade pitch angles, and temperature sensors 125 may be employed to provide ambient temperature. The resultant generator speed, electrical power, blade pitch angle(s) and current ambient temperature information may be provided to the control system in similar fashion to the rotor speed and wind speed information described herein.

**[0023]** A preferred method for estimation of wind speed according to one embodiment requires measurements of electrical power, generator speed, blade pitch

angles, and ambient temperature. Measurement of ambient temperature is employed according to one aspect for calculation/estimation of air density, which may alternatively be measured directly via more expensive sensors.

**[0024]** In some configurations and referring to Figure 3, an exemplary control system 300 for wind turbine 100 includes a bus 302 or other communications device to communicate information. Processor(s) 304 are coupled to bus 302 to process information, including information from sensors identified herein to measure rotor/generator speed, electrical power, blade pitch angles, ambient temperature, and effective wind speed. Control system 300 further includes random access memory (RAM) 306 and/or other data storage device(s) 308. RAM 306 and data storage device(s) 308 are coupled to bus 302 to store and transfer information and instructions to be executed by processor(s) 304. RAM 306 (and also data storage device(s) 308, if required) can also be used to store temporary variables or other intermediate information during execution of instructions by processor(s) 304. Control system 300 may also include read only memory (ROM) and or other static storage device (s) 310, which is coupled to bus 302 to store and provide static (i.e., non-changing) information and instructions to processor(s) 304. Input/output device(s) 312 can include any device known in the art to provide input data to control system 300 and to provide predetermined control outputs. Instructions are provided to memory from a storage device, such as magnetic disk, a read-only memory (ROM) integrated circuit, CD-ROM, DVD, via a remote connection that is either wired or wireless providing access to one or more electronically-accessible media, etc. In some embodiments, hard-wired circuitry can be used in place of or in combination with software instructions. Thus, execution of sequences of instructions is not limited to any specific combination of hardware circuitry and software instructions.

**[0025]** Sensor interface 314 is an interface that allows control system 300 to communicate with one or more sensors such as described herein. Sensor interface 314 can be or can comprise, for example, one or more analog-to-digital converters that convert analog signals into digital signals that can be used by processor(s) 304. In one

embodiment, the sensor interface includes signals from a rotor speed determining device, anemometry from wind vane 128, electrical power sensor(s), blade pitch angle sensor(s), and ambient temperature sensor(s).

**[0026]** A method for operating a wind turbine 100 is illustrated according to one embodiment in the process flow diagram 400 shown in Figure 4. The embodied method assumes that the blades 108 behave according to models, which posit blade efficiency has not been compromised, to estimate the wind speed. According to one embodiment, operational control commences by programming a predetermined minimum rotor stall margin into the control system 300, as represented in step 401. According to one aspect, the rotor is said to be stalled if any increase in wind speed reduces the thrust on the rotor. According to a preferred embodiment, the rotor is said to be stalled if a decrease in the rotor speed causes a decrease in the aerodynamic torque produced by the rotor. Figure 5 illustrates a typical aerodynamic map of the torque coefficient,  $C_m$ , as a function of tip-speed ratio and blade pitch angle according to one embodiment. The calculation of the minimum blade angle, based on such curves, requires knowledge of the tip-speed ratio, that is, of the rotor speed and the wind speed. Rotor speed, as described herein, can be calculated from the measurement of generator speed. The wind speed can be estimated, measured in a single location and later time averaged, or measured spatially with a Lidar or Sodar instrument.

**[0027]** With continued reference to Figure 4, turbine condition sensors such as described herein are scanned via the control system sensor interface 314 to provide without limitation, current rotor/generator speed information, current electrical output power, current blade pitch angles, and current ambient temperature as represented in step 403.

**[0028]** Further, current effective wind speed is estimated via the control system 300 in response to wind condition sensor readings as represented in step 405.

**[0029]** Using the current estimated wind speed and rotor speed based on the information provided in steps 403 and 405, the current rotor stall margin is determined via control system 300 by calculating the distance from the current collective blade pitch to the minimum collective blade pitch angle that would cause the turbine to reach the rotor stall line according to modeled aerodynamic performance of the rotor blades under the current operating conditions, as represented in step 407.

**[0030]** If necessary, the control system may adjust the blade pitch of one or more rotor blades 108 in response to the minimum collective blade pitch angle determined in step 407 to provide a collective blade pitch angle greater than or equal to the collective blade pitch necessary to maintain the predetermined minimum rotor stall margin according to the modeled aerodynamic performance of the rotor blades, as represented in step 409.

**[0031]** While the above has been described as determining the wind speed and the rotor speed directly from the corresponding systems or instruments, the wind speed and rotor speed may be provided from other locations or systems, such as weather monitoring stations, weather predictors, from a wind plant central monitoring/control, from predicted weather conditions, from externally mounted monitoring devices, from instruments mounted on other areas of the wind turbine or elsewhere in the wind turbine plant, such as directly on the blades, or by other methods or systems suitable for providing wind speed and/or rotor speed and/or other parameters suitable for calculating tip speed ratios.

**[0032]** Operation of the collective blade pitch angle at angles equal to or above the minimum blade pitch determined in step 409 provides operation that reduces or eliminates aerodynamic stall conditions resulting from, without limitation, low density air operation conditions susceptible to aerodynamic stalling.

**[0033]** While only certain features of the invention have been illustrated and described herein, many modifications and changes will occur to those skilled in the art. It

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is, therefore, to be understood that the appended claims are intended to cover all such modifications and changes as fall within the true spirit of the invention.

## CLAIMS:

1. A method for operating a wind turbine comprising:  
providing a wind turbine comprising a control system, predetermined turbine sensors, and at least one rotor blade having an adjustable pitch angle that is adjusted via the control system;  
programming the control system to adjust a blade pitch angle of one or more rotor blades, according to modeled aerodynamic performance of the rotor blades, in order to maintain continuous operation of the wind turbine without transitions to a stalled mode;  
scanning the predetermined turbine sensors via the control system to provide current conditions experienced by the wind turbine; and  
adjusting a blade pitch angle of one or more rotor blades in response to the current conditions experienced by the wind turbine to provide a blade pitch angle that is greater than or equal to a blade pitch angle necessary to maintain a predetermined minimum rotor stall margin, according to the modeled aerodynamic performance of the rotor blades, such that continuous operation of the wind turbine is maintained without transitions to the stalled mode.
2. The method according to claim 1, wherein the predetermined minimum rotor stall margin is calculated from a coefficient of torque curve as a function of rotor blade tip-speed ratio and rotor blade pitch angle.
3. The method according to claim 1, wherein the predetermined minimum rotor stall margin is calculated from a coefficient of thrust curve as a function of rotor blade tip-speed ratio and rotor blade pitch angle.
4. The method according to claim 1, wherein programming the control system comprises programming the predetermined minimum rotor stall margin into the control system.

5. The method according to claim 1, wherein the predetermined turbine sensors comprise one or more rotor speed sensors, one or more blade pitch angle sensors, one or more electrical power sensors, and one or more ambient temperature sensors.

6. The method according to claim 1, wherein the predetermined turbine sensors comprise one or more wind speed sensors, and one or more rotor speed sensors.

7. The method according to claim 1, wherein the current conditions experienced by the wind turbine comprise estimated wind speed and rotor speed.

8. The method according to claim 1, wherein the current conditions experienced by the wind turbine comprise measured wind speed and rotor speed.

9. The method according to claim 1, further comprising calculating a current rotor stall margin in response to the current conditions experienced by the wind turbine.

10. The method according to claim 9, further comprising adjusting a blade pitch angle of one or more rotor blades in response to the calculated current rotor stall margin.

11. A wind turbine comprising:  
at least one rotor blade having an adjustable pitch angle;  
one or more turbine sensors; and  
a control system programmed to adjust a blade pitch angle of one or more rotor blades, according to modeled aerodynamic performance of the rotor blades, in order to maintain continuous operation of the wind turbine without transitions to a stalled mode.

12. The wind turbine according to claim 11, wherein the control system is further programmed with a predetermined minimum rotor stall margin.

13. The wind turbine according to claim 12, wherein the predetermined minimum rotor stall margin is based on a coefficient of torque curve as a function of rotor blade tip-speed ratio and rotor blade pitch angle, a coefficient of thrust curve as a function of rotor blade tip-speed ratio and rotor blade pitch angle, or a combination thereof.

14. The wind turbine according to claim 12, wherein the control system is further programmed to adjust a blade pitch angle of one or more rotor blades in response to current conditions experienced by the wind turbine to provide a blade pitch angle that is greater than or equal to a blade pitch angle necessary to maintain the predetermined minimum rotor stall margin, according to the modeled aerodynamic performance of the rotor blades.

15. The wind turbine according to claim 14, wherein the current conditions experienced by the wind turbine comprise estimated wind speed and rotor speed.

16. The wind turbine according to claim 14, wherein the current conditions experienced by the wind turbine comprise measured wind speed and rotor speed.

17. The wind turbine according to claim 11, wherein the control system is further programmed to calculate a current rotor stall margin in response to the current conditions experienced by the wind turbine.

18. The wind turbine according to claim 17, wherein the control system is further programmed to adjust a blade pitch angle of one or more rotor blades in response to the calculated current rotor stall margin.

19. The wind turbine according to claim 11, wherein the one or more turbine sensors comprise at least one rotor speed sensor, at least one blade pitch angle sensor, at least one electrical power sensor, and at least one ambient temperature sensor.

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20. The wind turbine according to claim 11, wherein the one or more turbine sensors comprise one or more wind speed sensors, and one or more rotor speed sensors.

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Figures: S, 1 page

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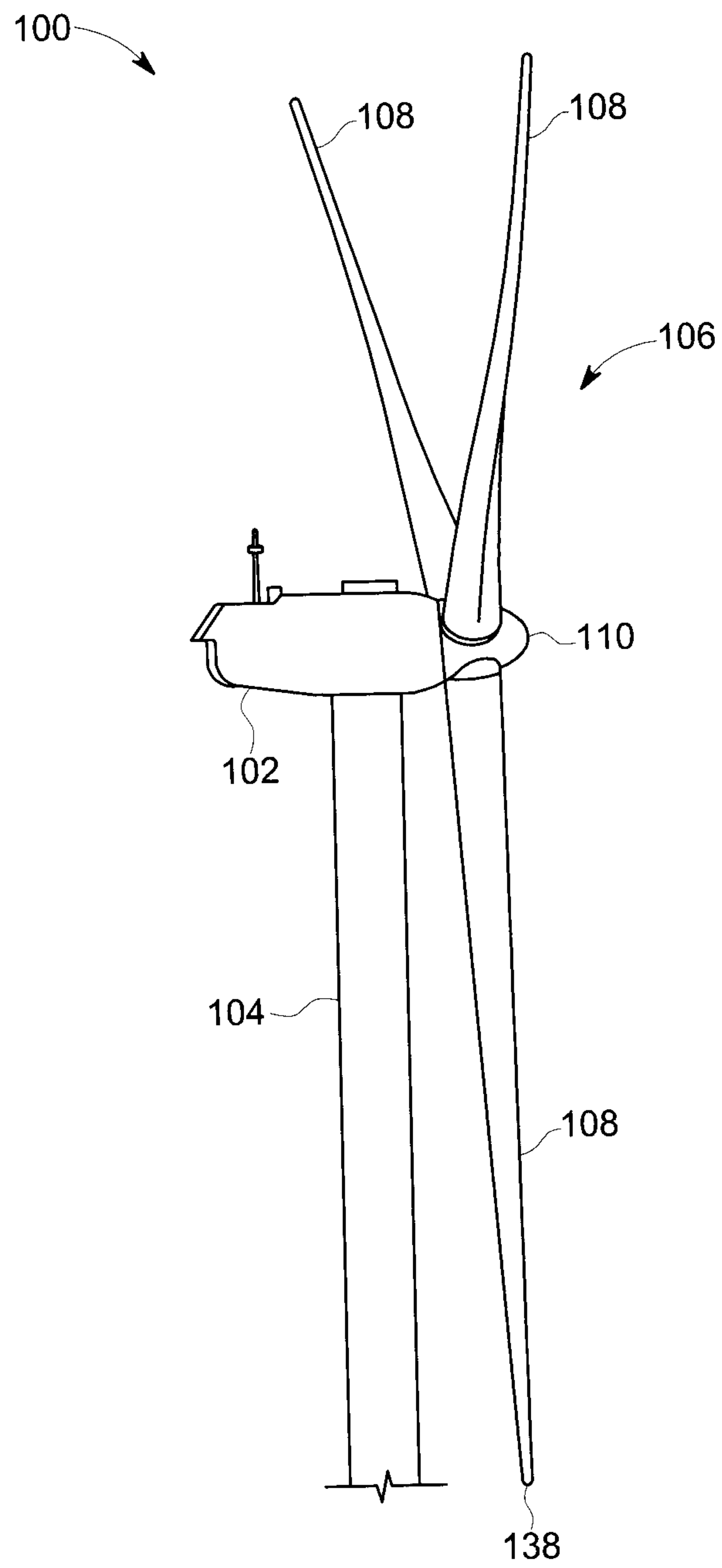


FIG. 1

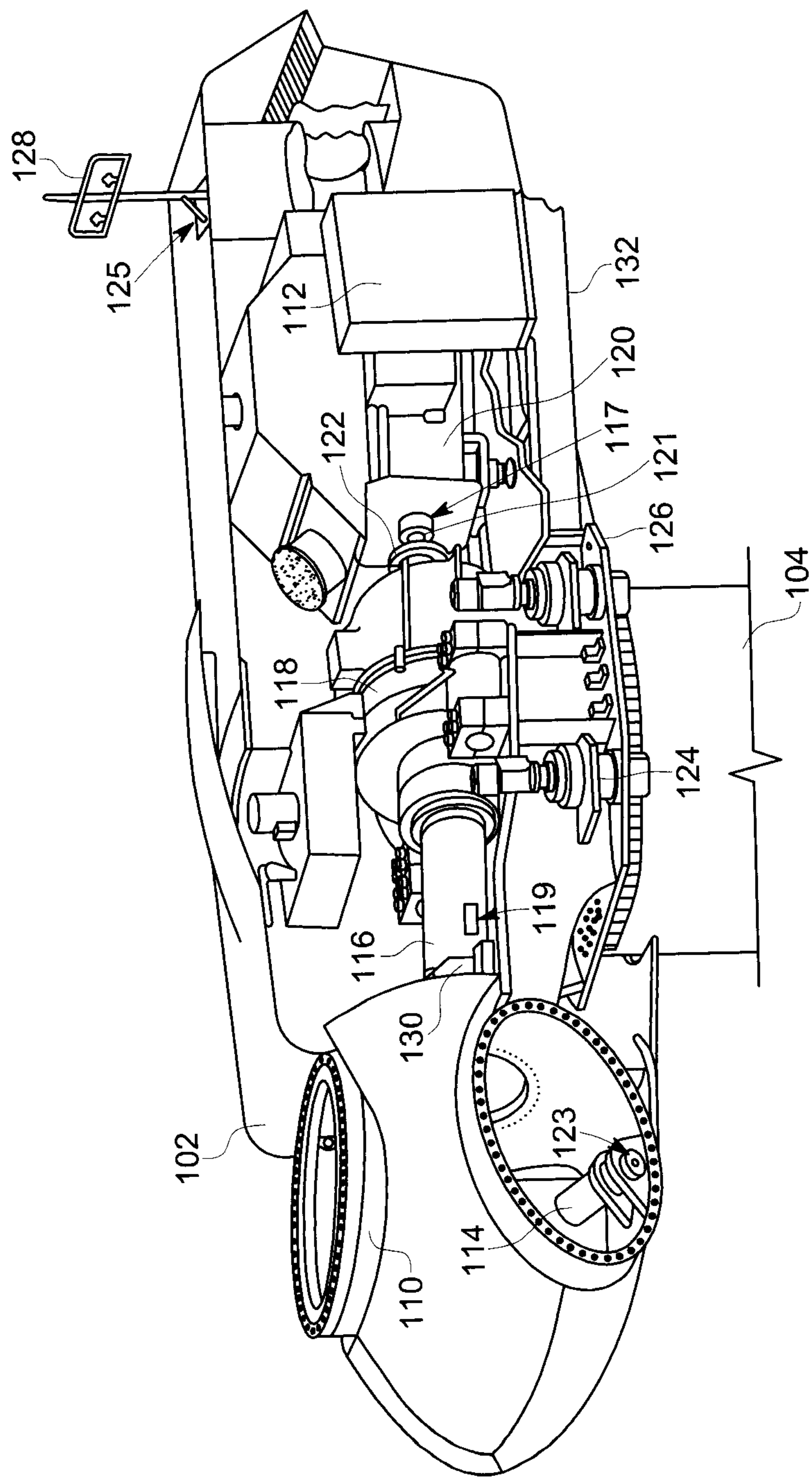


FIG. 2

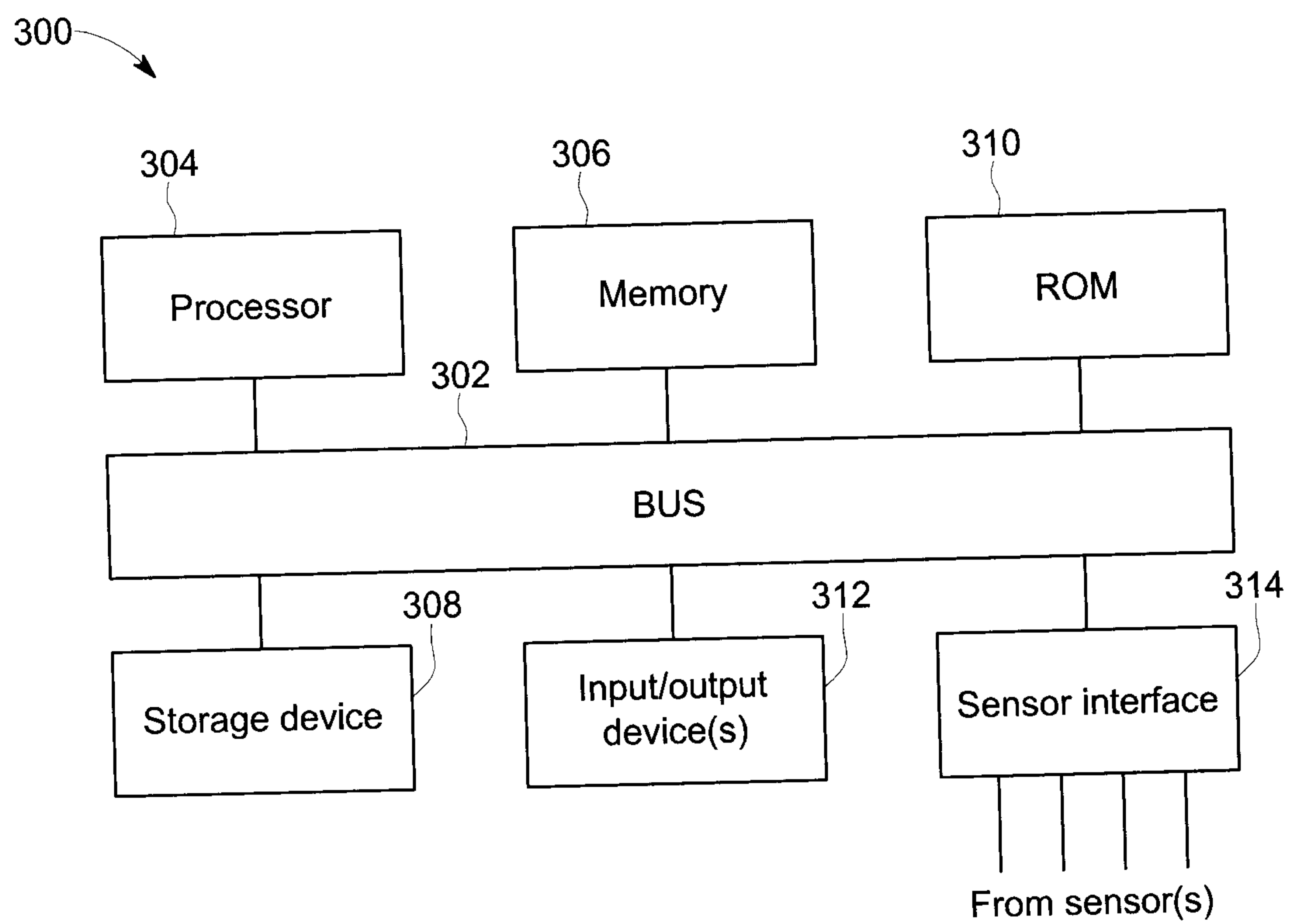


FIG. 3

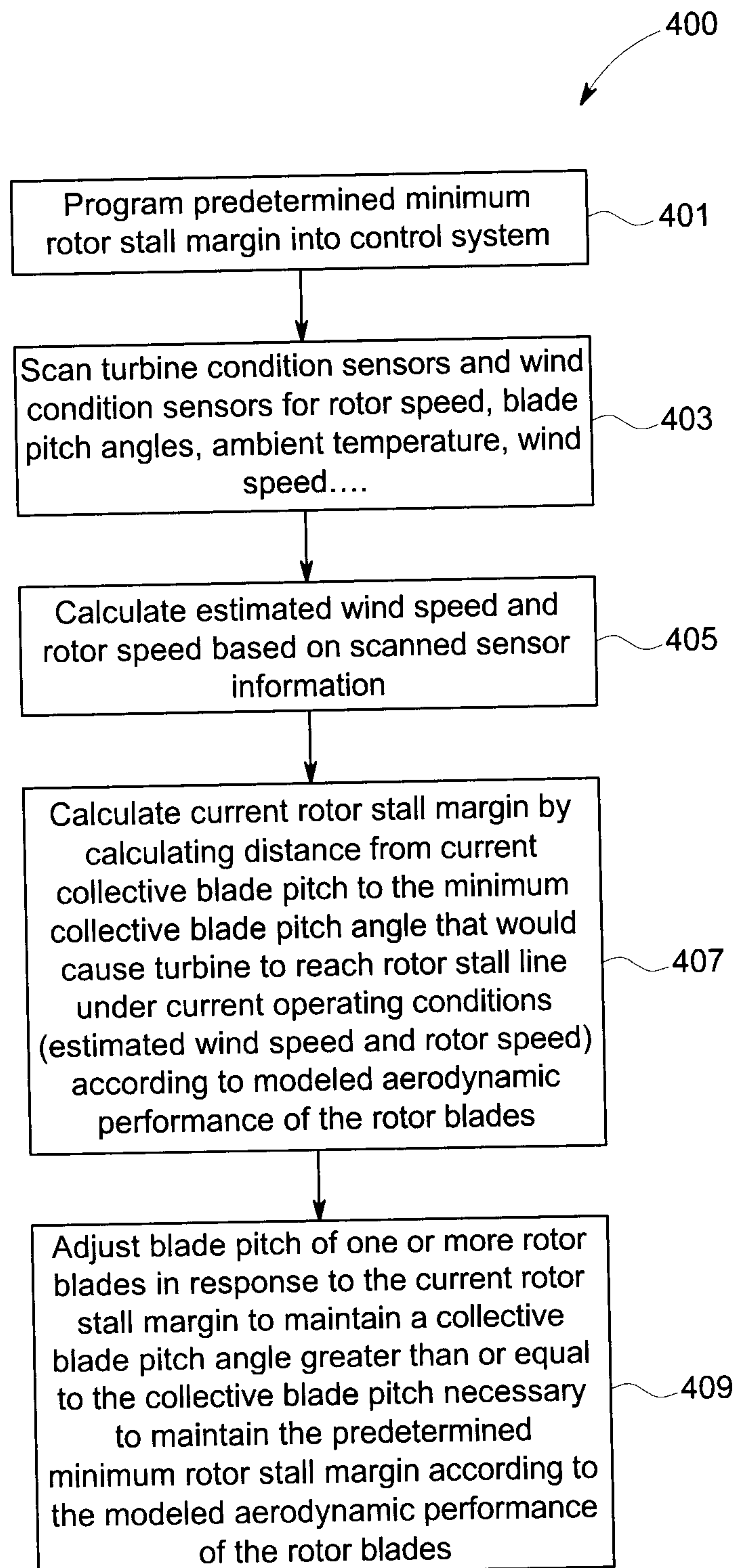


FIG. 4

400

Program predetermined minimum rotor stall margin into control system

401

Scan turbine condition sensors and wind condition sensors for rotor speed, blade pitch angles, ambient temperature, wind speed....

403

Calculate estimated wind speed and rotor speed based on scanned sensor information

405

Calculate current rotor stall margin by calculating distance from current collective blade pitch to the minimum collective blade pitch angle that would cause turbine to reach rotor stall line under current operating conditions (estimated wind speed and rotor speed) according to modeled aerodynamic performance of the rotor blades

407

Adjust blade pitch of one or more rotor blades in response to the current rotor stall margin to maintain a collective blade pitch angle greater than or equal to the collective blade pitch necessary to maintain the predetermined minimum rotor stall margin according to the modeled aerodynamic performance of the rotor blades

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